Radiation Damage Parameters for SiC/SiC Composite Structure in Fusion Nuclear Environment

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November 2002

UWFDM-1198

Presented at the 15th ANS Topical Meeting on Technology of Fusion Energy, 17-21 November 2002, Washington DC; published in *Fusion Science and Technology* 44, 150 (2003).

RADIATION DAMAGE PARAMETERS FOR SiC/SiC COMPOSITE STRUCTURE IN FUSION NUCLEAR ENVIRONMENT

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ABSTRACT

The radiation effects in the fiber, matrix, and interface components of the SiC/SiC composite material represent an important input for lifetime assessment. The relative values of these parameters are different for the various constituents of the composite. Neutronics calculations were performed to determine the radiation damage parameters in the fiber/matrix and the candidate interface materials. The radiation damage parameters were calculated for both the carbon and silicon sublattices. The radiation damage parameters were evaluated for representative candidate breeding blankets. The breeder and/or coolant such as $Pb_{83}Li_{17}$*, Flibe and* Li_2O *affect the radiation damage parameters by impacting the neutron spectrum. The results provide an essential input for SiC/SiC composite lifetime assessment. The impact of the unique features of inertial fusion systems on damage parameters are identified and should be accounted for in structure lifetime assessment of structure used in such systems.*

I. INTRODUCTION

SiC/SiC composites have been considered as structural material for the first wall (FW) and blanket in fusion power plants.[1] Their low induced radioactivity and decay heat and possible high temperature operation could help improve the attractiveness of fusion power plants. However, several critical issues are under investigation including fabrication and joining and performance at high temperature and under irradiation. The lifetime of such materials in the fusion radiation environment has been a major critical issue. The radiation effects in the fiber, matrix, and interface components of the composite material represent an important input for lifetime assessment. In this work, neutronics calculations were performed to determine the radiation damage parameters for the SiC fiber/matrix and the candidate interface materials. The radiation damage parameters were calculated for both the carbon and silicon sublattices.

Different breeding blanket concepts that utilize the SiC/SiC composite as structural material were used in several fusion power plant conceptutial design studies. The ARIES-AT[2] and TAURO[3] conceptual designs have FW/blankets that are self-cooled by $Pb_{83}Li_{17}$ eutectic (LiPb). The APEX study[4] also considered liquid wall blanket concepts that are self-cooled by the molten salt Flibe $[(BeF_2)(LiF)_2]$. A separate beryllium multiplier is required to achieve adequate tritium breeding in such blankets. The ARIES-IV[5] and DREAM[6] conceptual designs have FW/blankets that utilize the solid breeder Li_2O, beryllium multiplier, and helium coolant. The breeder and/or coolant such as $Pb_{83}Li_{17}$, Flibe and Li_2O in addition to the Be multiplier affect the radiation damage parameters by impacting the neutron flux and spectrum. Calculations were performed to assess the impact of the breeding blanket concept. The concepts considered are LiPb/SiC, Flibe/Be/SiC, and Li_2O/Be/He/SiC. The radiation damage parameters were evaluated for these representative candidate breeding blankets.

II. CALCULATION MODEL

The damage parameters calculated are the atomic displacement rate, the helium production rate, the hydrogen production rate and the total transmutation or burnup rate. The ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system[7] was used utilizing the most recent version of the FENDL-2 data library.[8] The cross section library includes all partial reaction cross sections required to determine gas production and transmutations. Although the code does not include contributions from multiple-sequence daughter product reactions, the difference was found to be negligible for SiC except for hydrogen production in C (a factor of 2) which produced a very small overall increase in the calculated SiC hydrogen production. The library includes the damage energy cross sections needed to determine the atomic displacements. The displacement energies of materials are dependent on the bonding. We determined the dpa cross sections using the recommended average displacement energies for the Si and C sublattices of 40 and 20 eV, respectively.[9]

The inboard (IB) and outboard (OB) regions are modeled simultaneously to properly account for the toroidal effects. We used the ARIES-AT configuration[2] with a 5.2 m major radius and IB and OB FW radii of 3.85 m and 6.55 m, respectively. The model includes a 5 mm thick SiC/SiC composite structural FW followed by a breeding blanket. The LiPb/SiC blanket option consists of

86% LiPb and 14% SiC/SiC. For the blanket utilizing Flibe, separate beryllium should be added to ensure tritium self-sufficiency. In this case, we use a 6 cm thick front blanket zone consisting of 60% Be, 35% Flibe and 5% SiC/SiC. The bulk of the blanket includes 86% Flibe and 14% SiC/SiC structure. For the blanket concept utilizing the Li_2O solid breeder with He gas cooling, a front 6 cm thick neutron multiplier zone consisting of 60% Be, 33% He and 7% SiC/SiC is used with the bulk of the blanket including 50% Li_2O, 35% He coolant and 15% SiC/SiC structure. The total blanket thickness for the three concepts is 80 cm in the OB region and 40 cm in the IB region. While natural lithium is used in the Flibe and Li_2O, the Li in LiPb is enriched to 90% ^{6}Li. The neutron wall loading is normalized to 10 MW/m^2 in the OB side and 6.5 MW/m^2 in the IB side. The calculated local tritium breeding ratio (TBR) values are 1.35, 1.45, and 1.39 for the LiPb, Flibe and Li_2O blankets, respectively, implying that tritium self-sufficiency can be assured.

III. DAMAGE PARAMETERS IN THE LiPb/SiC FW/BLANKET

The SiC/SiC damage parameters were determined at the FW and as a function of depth in the blanket. Table I gives the peak radiation damage parameters in the Si and C sublattices at midplane in the OB and IB regions. The highest damage parameters occur in the OB region at midplane. The leading interface material candidates are graphite for near-term applications, and multilayer or porous SiC for longer-range applications. The damage parameters for the SiC interface material are identical to those for the SiC fiber/matrix. The damage parameters for the graphite interface material are the same as those for the C sublattice of SiC except for the dpa due to the higher (30 eV) displacement energy of C in graphite.

Table I. Peak Radiation Parameters in the Si and C Sublattices at Midplane

	C Sublattice		Si Sublattice	
	OB	IB	OB	IB
dpa/FPY	163	160	147	137
He appm/FPY	26,460	19,300	6,680	4,900
H appm/FPY	5	4	12,155	8,936
% Burnup/FPY	0.93%	0.68%	1.88%	1.38%

Figure 1 shows the radial variation of the dpa rate in the C and Si sublattices of the SiC fiber/matrix and in the graphite interface material at midplane in the OB region. The results indicate that the dpa rate in the C sublattice is larger than in the Si sublattice of the SiC fiber/matrix. The difference increases as one moves deeper in the blanket. The dpa rate in the graphite interface material is 33% lower than in the C sublattice of the SiC.

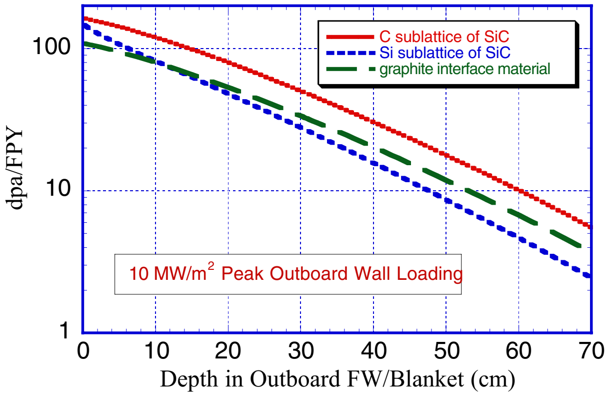

Fig. 1. Radial Variation of dpa Rate in the OB LiPb/SiC Blanket at Midplane.

Figure 2 gives the radial variation of helium production rate in the OB blanket at midplane. He production rate in the C sublattice of the SiC fiber/matrix and the graphite interface material is about a factor of 4 higher than in the Si sublattice of the SiC fiber/matrix. This is dominated by the $(n,n'3\alpha)$ reaction. The average He production rate in the graphite interface is 60% higher than the average He production rate in the SiC fiber/matrix. The He production rates drop by an order of magnitude in ~20 cm of the LiPb/SiC blanket. Significant hydrogen production occurs in the silicon with a negligible amount produced in the carbon. The H production rate in the graphite interface material and the C sublattice of the SiC fiber/matrix is more than three orders of magnitude lower than in the Si sublattice of the SiC fiber/matrix. This is due to the very high threshold energy of 13.6 MeV for the (n,p) reaction with carbon compared to 4 MeV for silicon.

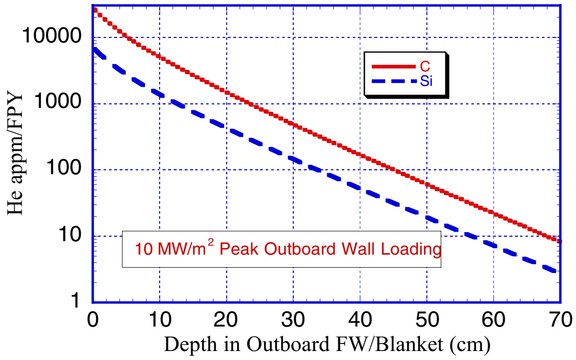

Fig. 2. Radial Variation of He Production Rate in the OB LiPb/SiC Blanket at Midplane.

Figure 3 illustrates the radial variation of the burnup rate in the OB blanket at midplane for both C and Si. The burnup rate of the Si sublattice is twice that for the C sublattice of the SiC fiber/matrix and graphite interface material. The burnup rates drop by an order of magnitude in ~20 cm of the LiPb/SiC blanket. The burnup is equivalent to introducing impurities in the sublattices of the SiC. Property degradation depends on the kind of impurities introduced. Transmutation of Si produces primarily Al with smaller amount of Mg. The main transmutation product for C is Be with some Li produced from multiple neutron reactions. The nonstoichiometric burnup of Si and C is expected to be worse than stoichiometric burnups and could be an important issue for lifetime assessment.

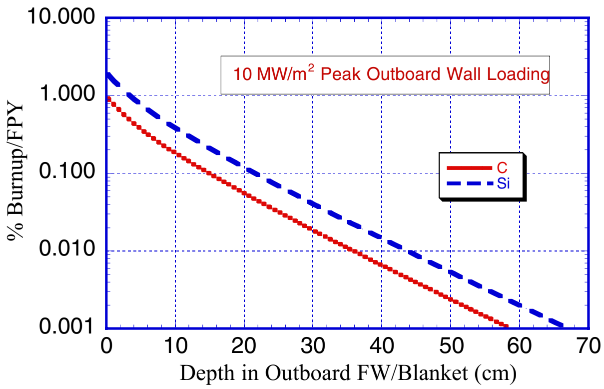

Fig. 3. Radial Variation of Burnup Rate in the OB LiPb/SiC Blanket at Midplane.

IV. IMPACT OF BREEDING BLANKET CONCEPT ON DAMAGE PARAMETERS IN SiC/SiC

Table II gives the peak FW radiation damage parameters in the Si and C sublattices at midplane in the OB and IB regions for the Flibe/Be/SiC FW/blanket concept. Comparing these peak damage parameters to those in the case of the LiPb/SiC FW/blanket indicates that the peak dpa rates are lower by 25-45% when Be and Flibe are used in the blanket. On the other hand, the gas production and burnup rates are higher by 3-10%. This is attributed to the larger fast neutron flux (E>0.1 MeV) at the FW when Pb is in the blanket.

Table II. Peak Radiation Damage Parameters in Si and C Sublattices at Midplane for the Flibe/Be/SiC FW/Blanket

	C Sublattice		Si Sublattice	
	OB	IB	OB	IB
dpa/FPY	89	86	109	94
He appm/FPY	27,140	19,755	7,316	4,444
H appm/FPY	5	4	13,226	9, 832
% Burnup/FPY	0.99%	0.73%	2.05%	1.53%

Table III gives the peak radiation damage parameters in the Si and C sublattices at midplane in the OB and IB regions for the Li_2O/Be/He/SiC FW/blanket concept. Comparing these peak damage parameters to those in the case of the Flibe/Be/SiC FW/blanket indicates that the peak dpa rates are slightly higher by 3-6%. On the other hand, the gas production and burnup rates are identical. The Be used in the front blanket zone behind the FW knocks down the neutron energies below the threshold energies for the gas production reactions. Since the same amount of Be is used in the zone behind the FW, identical gas production and burnup rates are obtained in the FW.

Table III. Peak Radiation Damage Parameters in Si and C Sublattices at Midplane for the Li_2O/Be/He/SiC FW/Blanket

	C Sublattice		Si Sublattice	
	OB	IB	OB	IB
dpa/FPY	93	91	112	97
He appm/FPY	27,140	19,755	7,316	4,444
H appm/FPY	5	4	13,226	9, 832
% Burnup/FPY	0.99%	0.73%	2.05%	1.53%

The results imply that if the dpa is the lifetime driver for the SiC/SiC composite structure, the lifetime will be significantly longer in Flibe/Be/SiC or Li_2O/Be/He/SiC FW/blanket concepts than in a LiPb/SiC blanket operating at the same neutron wall loading. On the other hand, if gas production or burnup determine the lifetime, the lifetime will be slightly longer in a LiPb/SiC blanket.

V. UNIQUE FEATURES OF INERTIAL CONFINEMENT SYSTEMS THAT IMPACT LIFETIME ASSESSMENT

SiC/SiC composite structure has also been considered in inertial fusion energy (IFE) conceptual design studies [10]. While neutron wall loading values are comparable to those in magnetic fusion energy (MFE) systems there are significant geometrical, spectral and temporal differences that affect the radiation damage levels with impact on lifetime assessment [11]. While a cylindrical or toroidal chamber surrounds a volumetric distributed source in MFE systems, a nearly spherical chamber in IFE plants surrounds a point neutron source. As a result, source neutrons in IFE chambers impinge on the FW/blanket in a more perpendicular direction. This leads to lower FW radiation damage parameters with smaller radial gradient in the blanket for the same neutron wall loading. Simple scaling of radiation effects with neutron wall loading is inappropriate. Fusion neutron interactions in the highly compressed target result in considerable softening of the neutron spectrum incident on the FW/blanket in IFE chambers. These neutrons can have average energies in the range 10-12 MeV. These effects together with the temporal effects in the pulsed IFE chamber impact the radiation damage parameters in the FW/blanket.

In an IFE chamber, the neutron source has a pulsed nature because of the very short burn time (10-100 ps). The energy spectrum of the neutrons emanating from the target results in time of flight spread with most of the neutrons arriving at the FW over a time period of several tens of nanoseconds. In addition, backscattering from the blanket extends the period over which a particular radiation effect takes place. This period is larger for radiation effects produced by lower energy neutrons and at locations deeper in the blanket. As a result, the time spread of dpa rate is significantly larger than that for gas production and transmutation rates.[12] The time spread ranges from a few nanoseconds to a few microseconds depending on the damage parameter and depth in blanket. Peak instantaneous damage rates in IFE FW/blanket are ~5 to 8 orders of magnitude higher than the steady state damage rates produced in MFE systems. In addition, the difference in time spread results in higher instantaneous He/dpa ratios in IFE systems compared to MFE systems.

VI. LIFETIME CONSIDERATIONS

The useful lifetime of SiC/SiC composites in a fusion neutron environment can now only be speculated. Several factors may seriously degrade mechanical properties, or produce unacceptable dimensional change. In the last decade the development of SiC/SiC for nuclear systems has focused on producing a composite capable of withstanding a fission neutron environment, primarily high neutron and gamma doses. This work has led to the development of a composite manufactured from essentially stoichiometric fiber, matrix, and interface[13] which shows no degradation to an equivalent fusion neutron fluence of about 1 MW-y/m^2. Since the thermomechanical properties saturated before this neutron dose it can be argued that these materials will remain unaffected at higher dose levels. The lifetime question then comes down to the effect of the high-energy transmutants of not only He, but also metallics such as Al, Be, and Mg produced. Moreover, transmutations will also produce an unbalanced stoichiometry that must be considered.

It is known that low melting temperature metallics affect the mechanical properties of SiC. Degradation in non-irradiated strength and enhanced creep at high temperatures occur due to the presence of free silicon.[14] Other work[15,16] clearly indicates that the presence of free silicon (or other metallic sintering aids) causes anisotropic dimensional change under irradiation resulting in strength reduction at very low neutron dose (~0.1 MW-y/m^2). Following the calculations presented in this paper, transmutation of silicon occurs at about twice the rate of carbon, producing excess carbon in the crystal. Unlike free silicon, carbon is not expected to segregate to grain boundaries and degrade properties. However, the other metallics produced by transmutation still may be problematic.

Helium is the likely life-limiting factor for SiC. Not only will the removal of Si and C from the lattice degrade properties, the transmuted helium will likely cause unacceptable consequences. There has been limited study of high levels of helium on the mechanical properties of SiC[17,18] and SiC composites.[19] For the case of monolithic materials, helium was produced through the $^{10}B(n,\alpha)$ reaction. Boron acted as a sintering aid and was located at the grain boundaries. In one case, post-irradiation bend strength was seen to decrease.[17] However, this was more likely due to the anisotropic swelling of the SiC and grain boundary phases rather than a response to the presence of He. A recent study[18] implanted up to 1000 appm He prior to fission neutron irradiation yielding a fusion relevant He/dpa ratio. Mechanical properties were then measured with the conclusion that the presence of the helium had no additional effect.

The problem common to all previous work on He effects in SiC is the very different manner in which the helium finds its way into the SiC than would occur in fusion. Production of helium in the presence of neutron damage will cause large, temperature-dependent swell. Based on previous TEM studies of bubble formation under helium irradiation and subsequent annealing,[20] formation of helium bubbles is not expected below ~1000°C. Moreover, Sasaki[17] showed that helium bubbles begin to form at ~1400°C near grain boundaries for 650°C neutron irradiated, sintered SiC with ~2000 appm helium produced via the $^{10}B(n,\alpha)$ reaction. While it is clear that bubble formation due to helium will produce swelling in SiC, it is not known what the magnitude of the swelling will be, though it will certainly scale with burnup. Until this is known, an actual estimate of lifetime can only be a guess.

The high instantaneous damage rates present in IFE can lead to significant changes in the microstructure of the material. The high instantaneous dpa rates could result in higher recombination rates with the void growth being inhibited and swelling decreased as compared to the equivalent continuous irradiation case.[21] Another difference that should be taken into account in IFE systems is that damage from X-rays, neutrons and ion debris occur over different time scales unlike in MFE systems where damage from neutrons and radiation from the plasma occur simultaneously. It is therefore essential to account for these unique features for accurate prediction of the structure lifetime in IFE systems.

VII. SUMMARY AND CONCLUSIONS

Neutronics calculations have been performed to determine the radiation damage parameters in the fiber, matrix, and interface components of the SiC/SiC composite structural material employed in candidate breeding blankets. The radiation damage parameters were calculated for both the carbon and silicon sublattices. The breeder blanket concepts considered included LiPb/SiC, Flibe/Be/SiC, and Li_2O/Be/He/SiC.

Nearly similar atomic displacement damage rates take place in Si and C. Helium production in C is about a factor of 4 larger than that in Si. On the other hand, significant hydrogen production occurs in Si with negligible amount in C. As a result, the burnup of Si is about a factor of 2 more than that of C. Property degradation depends on the kind of impurities introduced by transmutations. The transmutation products include Al, Mg, Li, and Be. The nonstoichiometric burnup of Si and C is expected to be worse than stoichiometric burnups and could be an important issue for SiC. Damage parameters were compared in candidate blanket concepts. We conclude that if the dpa is the lifetime driver for SiC/SiC structure, the lifetime will be significantly longer in Flibe/Be/SiC or Li_2O/Be/He/SiC FW/blanket concepts than in a LiPb/SiC blanket operating at the same neutron wall loading. On the other hand, if gas production or burnup determine lifetime, the lifetime will be slightly longer in a LiPb/SiC blanket. In inertial confinement systems, the geometrical, spectral, and temporal features influence the structure damage parameters. The pulsed nature of IFE systems results in very large instantaneous damage parameters with the dpa and gas production being affected differently. It is therefore essential to account for these unique features for accurate prediction of the structure lifetime in IFE systems.

The results given here provide an essential input for SiC/SiC composite lifetime assessment. The impact of damage parameters on properties and lifetime needs to be assessed. However, a determination of the effect of fusion-neutron transmutations on the thermomechanical properties of SiC will be required to set a lifetime for SiC components. It is speculated that the lifetime will be set by swelling produced by transmuted helium.

ACKNOWLEDGEMENT

Funding for this work was provided by the U.S. Department of Energy.

REFERENCES

[1] R. Raffray, et al., "Design and Material Issues for High Performance SiC/SiC-Based Fusion Power Cores," *Fusion Eng. and Design*, **55**, 55 (2002).

[2] A.R. Raffray, L. El-Guebaly, S. Gordeev, et al., "High Performance Blanket for ARIES-AT Power Plant," Proc. 21st Symposium on Fusion Technology, September 2000, Madrid, Spain.

[3] H. Golfier et al., "Progress on the TAURO Blanket System," Proc. 21st Symposium on Fusion Technology, September 2000, Madrid, Spain.

[4] M.A. Abdou, A. Ying, N. Morley, et al., "On the Exploration of Innovative Concepts for Fusion Chamber Technology," *Fusion Eng. and Design*, **54**, 181 (2001).

[5] L.A. El-Guebaly, "Neutronics Aspects of ARIES-II and ARIES-IV Fusion Power Reactors," *Fusion Technology*, **21**, 2128 (1992).

[6] S. Nishio, S. Ueda, I. Aoki, et al., "Improved Tokamak Concept Focusing on Easy Maintenance," *Fusion Eng. and Design*, **41**, 357 (1998).

[7] R.E. Alcouffe, R. Baker, F. Brinkley, et al., "DANTSYS 3.0, A Diffusion Accelerated Neutral Particle Transport Code System, LA-12969-M, Los Alamos National Laboratory (June 1995).

[8] M. Herman and H. Wienke, "FENDL/MG-2.0 and FENDL/MC-2.0, The Processed Cross-Section Libraries For Neutron-Photon Transport Calculations," Report IAEA-NDS-176, International Atomic Energy Agency (March 1997).

[9] S.J. Zinkle and C. Kinoshita, "Defect Production in Ceramics," *J. Nucl. Mater.*, **251**, 200 (1997).

[10] L. Wagner, et al., "Inertial Fusion Energy Reactor Studies: Prometheus-L and Prometheus-H," IAEA Technical Meeting and Workshop on Fusion Reactor Design and Technology, 13-17 Sept. 1993.

[11] M. Sawan, "Geometrical, Spectral and Temporal Differences between ICF and MCF Reactors and Their Impact on Blanket Nuclear Parameters," *Fusion Technology*, **10**, 1483 (1986).

[12] M. Sawan, G. Moses, and G. Kulcinski, "Time-Dependent Neutronics Analysis for the HIBALL Heavy Ion Beam Fusion Reactor," *Nuclear Technology/Fusion*, **2**, 215 (1982).

[13] L. Snead, T. Hinoki, and Y. Katoh, "Strength of Neutron Irradiated Silicon Carbide and Silicon Carbide Composites," Submitted to *J. Nucl. Mater.*, 2002.

[14] E. Lara-Curzio, Ph.D Thesis, Dept. of Materials Science, Rensselaer Polytechnic Institute, 1992.

[15] R.J. Price, G.R. Hopkins, *J. Nucl. Mater.*, **108-109**, 732 (1982).

[16] R. Matthews, *J. Nucl. Mater.*, **51,** 203 (1974).

[17] J.C. Corelli, J. Hoole, J. Lazzaro, and C.W. Lee, *J. Amer. Ceram. Soc.*, **66**, 529 (1983).

[18] L. Snead, et al., *J. Nucl. Mater.*, Accepted 2002.

[19] A. Hasegawa, M. Sairo, S. Nogami, K. Abe, and R.H. Jones, *J. Nucl. Mater.*, **253,** 31 (1998).

[20] T. Suzuki, T. Yano, T. Mori, H. Miyazaki, and T. Iseki, *Fusion. Technology*, **27,** 314 (1995).

[21] M. Sawan, G. Kulcinski, and N. Ghoniem, "Production and Behavior of Point Defects in Pulsed Inertial Confinement Fusion Reactors," *J. Nucl. Mater.*, **103 & 104**, 109 (1981).